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THERMAL CONDUCTIVITY OF THE HUMAN BODY DURING IMMERSION AT THERMAL NEUTRALITY AND IN A COLD ENVIRONMENT

C. Boutelier, J. Timbal and J. Colin

Translation of "Conductance Thermique du Corps Humain en Immersion a la Neutralité Thermique et en Ambiance Froide," Arch. Sci. Physiol. 27 (1973) pp. 189-205

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16. Abstract

The thermal conductivity of the body immersed in water at thermal neutrality is found to be close to that observed in air, with only slight variations between individuals and no apparent effect due to the quantity of adipose tissue. In cold water, however, conductivity does depend on the fatness or thinness of the subject, since cutaneous vasoconstriction occurs, making use of the layer of subcutaneous fat to insulate the body center from the cold. The effect of cutaneous vasoconstriction is limited, however, and the muscular region is found to contribute to peripheral insulation, a phenomenon which has been considered a characteristic of adaptation to cold.

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THERMAL CONDUCTIVITY OF THE HUMAN BODY DURING IMMERSION AT THERMAL NEUTRALITY AND IN A COLD ENVIRONMENT

C. Boutelier, J. Timbal and J. Colin

Introduction *[/189]

In the equation representing the state of thermal stability of the body in a given environment:

$$M - H_{Res} = h_b \ (T_{re} - \bar{T}_s) \tag{1}$$

$(M-H_{Res})$ represents the heat losses from the skin, essentially due to convection in the case of immersion, $(T_{re} - \bar{T}_s)$ the temperature difference between the center and the surface of the skin, assuming the rectal temperature to be the average temperature of the center, and h_b, a magnitude dependent on the thermal properties of the tissues which is termed the conductivity or center-periphery heat exchange coefficient. This coefficient, the inverse of insulation, is the resultant of various channels which permit the flow of heat toward the body surface. Heat is transmitted to the skin by two processes: by conduction through the tissues and intercellular gaps and by blood convection (Burton, 1955). The exchange by conduction depends on the thermal conductivity of the various tissues and does not vary with temperature, while the exchange by blood convection is dependent on local blood flow rates and is therefore influenced by physical reactions — muscular activity, vasodilation, vasoconstriction, etc. — which modify them. As Burton proposes (1955), it may be assumed that these two channels of exchange operate in parallel, assuming, however, that the /190
exchanges occur in only one direction perpendicular to the surface of the body. In this case the conductivities may be added. Thus, even though the overall conductivity of the body is a practical

* Numbers in the margin indicate pagination in the foreign text.

concept for the analysis of heat exchange, it appears to be an extremely complex phenomenon, varying in response to a number of physical and anatomic factors. It may therefore assume widely varying values in a single given subject, depending on the ambient conditions and the physical reactions which they provoke, or, from one subject to the next, it may differ within a given environment for anatomic reasons such as the thickness of the subcutaneous fat. For this reason it is extremely important to stipulate the experimental conditions under which the thermal conductivity of the body has been measured. After an examination of the principle conductivity measurements given in the literature, we will present and discuss the results we have obtained during 52 immersion experiments performed on ten nude subjects immersed in thermally neutral baths.

II. Review of the Literature

Before entering on this review, we should point out that a number of investigators, after Burton (1955), consider the skin temperature to be equal or extremely close to the water temperature in immersion experiments. This is an inaccurate assumption, even with fairly high water flow rates, as shown by the experiments of Lefevre in 1901 and Boutelier in 1973, and which also may be deduced from the physics equations for heat exchange applied to the human body (Rapp, 1971). In addition, the surface temperatures vary with body region. These differences are due to thermal fluxes which vary according to body region, since the shape of the area has a strong influence on the convection coefficient. Thus there is a difference between average skin temperature and water temperature whose significance depends on the speed of the current and the temperature of the bath. To overlook this factor results in underestimation of the conductivity of the body and tends to minimize the variations in conductivity between individuals. However, the pattern of evolution of the conductivity in a cold environment remains unchanged or only slightly changed.

The first values for the conductivity of the skin and the subcutaneous tissue were obtained by Lefevre (1901). During remarkable direct calorimetric experiments, this investigator measured the heat loss by the body in baths at temperatures of 5, 12, 18, 24 and 30°C, and simultaneously recorded the cutaneous /191 and subcutaneous temperatures. In this way he calculated the conductivity of the skin and that of the subjacent tissue and showed that the conductivity of the skin decreases as the temperature of the bath drops from 30 to 5°C, but that that of the subcutaneous tissue simultaneously increases by a factor of six. This decrease in the conductivity of the skin can easily be explained by superficial vasoconstriction, but according to Burton (1955), the increase in the conductivity of the subcutaneous tissue is more difficult to interpret. He suggests that stability may not have been reached, and as a result, there are abnormal temperature gradients in the peripheral layer which allow for this increase. However, calculation of the overall conductivity of the periphery (skin and subcutaneous tissue) using the values given by Lefevre (Table 1):

$$h_{periphery} = \frac{h_{skin} \times h_{subcutaneous\ tissue}}{h + h_{skin/subcutaneous\ tissue}}$$

shows that the conductivity is weakest, 7W/m^2 °C, in a 30°C bath. It then progressively increases with the development of thermogenic reactions to combat cold as the temperature of the bath decreases. The peripheral conductivity values in the coldest baths are probably too low, however, since the length of exposure of the subject is too brief (15 min at 5°C). This evolutive pattern for conductivity in cold baths was observed by Burton and Bazett (1936), who showed that at a water temperature of approximately 33°C, the conductivity reaches a minimum with a value of 7.17 W/m^2 °C, and then gradually increases for lower water temperatures as the oxygen consumption increases. Craig and Dvorak (1966) and we ourselves (Boutelier et al., 1968) have obtained similar results during immersion experiments in calm water or water agitated only by shivering. Consequently it may be assumed that the effectiveness of shivering or exercise as a means of defense against cold is limited by the increase in the heat transfer capacity of the peripheral zone. This finding corroborates that of Keatinge (1960), who has shown that in water at 15°C, excercise significantly aggravates the drop in rectal temperature. Thus these results indicate that the effectiveness of peripheral vasoconstriction is quite limited, since according to Burton and Bazett (1936), it is unable to prevent an increase in metabolic rate in baths at temperatures less than 33°C.

The purpose of cutaneous vasoconstriction is not only to reduce heat exchange by blood convection, however. The arrangement of the cutaneous vessels seems to indicate that their nutritional function in regard to the structures of the skin is of slight importance in comparison with their thermoregulatory functions. The presence of arteriovenous anastomoses at all levels of the dermis makes it possible for the blood to avoid the superficial capillary layer when the cutaneous arterioles are under vasoconstriction. If the cold is sufficiently intense, the blood circulation in the skin may be completely short-circuited and the heat exchanges between the center and the skin will occur through the subcutaneous fat. It follows that there may be a wide variation in the conductivities of several subjects placed in the same environment (Winslow and Herrington, 1949). Thus in a cold /192
environment the conductivities of fat subjects are always lower than those of thin subjects. Beckman et al. (1956) have pointed out that the conductivity h_b may vary by a factor of 20 for various subjects subjected to the same cold environment. These differences are essentially due to variations in the thickness of the subcutaneous adipose tissue, since it is a widespread finding that fat men do not increase their heat production as much as thin men in a given environment. Thus Pugh and Edholm (1955), studying

the physiology of swimmers crossing the English Channel, have shown that these subjects have an unusually thick layer of subcutaneous fat and are capable of tolerating lower skin temperatures than thinner subjects. Baker and Farrington (1956) confirm this observation and point out that in a given environment, the thicker the cutaneous fold, the lower the surface temperature. Differences in body fat of between 1 and 19% result in differences of 0.7°C in rectal temperature and 3.3°C in average skin temperature after two hours of exposure to cold in the air at 15°C. Fat subjects have a higher rectal temperature than thin subjects, but a lower skin temperature. Buskirk et al. (1963), examining the role of body composition, particularly body fat, in metabolic response to cold, state that in order to determine the critical water temperature, i.e. the temperature below which there is an increase in oxygen consumption, one must first know the quantity of subcutaneous fat. The subjective sensation of cold is not changed, however. The minimum rectal temperature is directly related to the percentage of body fat, while the average skin temperature is in inverse proportion. In a given environment, the obese subject will thus have a relatively colder surface and a relatively warmer center than the thin subject. These results negate the opinion of Burton and a number of other investigators after him, who assume that in water, the skin temperature is uniform and so close to that of the water that the difference ($\bar{T}_s - T_{H_2O}$) may be overlooked in calculating the conductivity. One may therefore expect differences between local skin temperatures for a single given subject and differences between the average skin temperatures of several subjects immersed in baths at the same temperature.

The importance of the subcutaneous fat in tolerance to immersion in cold water has been clearly demonstrated by Cannon and Keatinge (1960). The fattest subjects tested by these investigators were able to stabilize their internal temperature in baths at 12°C, while stabilization was observed in the thin subjects only at much higher water temperatures (at least 24°C). Moreover, Keatinge (1960) has shown there to be a linear relationship between

the drop in rectal temperature and the increase in the temperature of the skinfold in a group of volunteers immersed for 30 minutes in water at 15°C. However, this investigator points out that some individual differences in rates of cooling cannot be explained by different skinfolds, but rather correspond to more or less intense peripheral circulatory reactions. This finding is comparable to those of Hammel (1963), Rennie et al. (1962) and Inoue (1972) on the racial differences which may occur in reactions to cold, either by adaptation (Indians, bushmen, /193
Australian aborigénes, Japanese) or by acclimatization (Korean diving women. Thus Rennie, comparing the reactions of diving women, Koreans and Americans to different bath temperatures, has shown that, despite their thinner skinfold, the diving women have a lower critical water temperature (30-31°C) than do American subjects (men and women). Similarly, Inoue (1972) has obtained lower critical water temperatures for Japanese than Americans. It therefore seems that in some cases peripheral vasoconstriction can reach the superficial part of the muscular region, which would participate in the insulation of the body. However, the small skinfold magnitudes measured by these investigators for extremely low conductivities also seem to indicate that a stable state is not reached. Inoue, for example, cites a conductivity of 3.34 W/m^2 °C in water at 24.7°C for a subject with an adipose layer 6.8 mm thick. This value is lower than that of men with skinfolds 27 mm thick (Cannon Keatinge, 1960), or an adipose layer 12.5 mm thick, according to our estimates. Without wishing to criticize the interpretation of vasoconstriction of the superficial muscular layers, it is possible that the methods of calculating the thickness of the subcutaneous fat are not completely comparable. The thickness of the subcutaneous adipose tissue is estimated by subtracting the thickness of the dermis and the epidermis from the measurements. Hammel, Rennie, Stolwijk and Hardy (1966) estimate the average thickness of the skin to be 2 mm. This is also the opinion of Bazett and McGlone (1927), based on the work of Murchov, who give the

following values for the skin of the thigh and forearm: epidermis 0.04-0.15 mm, epidermis and dermis 1.8-2 mm. However, temperature measurements which have been performed at various depths beginning at the skin surface have made it possible to locate a dermal subpapillary arterial network at a depth of 1 mm and a large venous network at approximately 1.6 mm. Thus we agree with Atkins and Wyndham (1969) that, rather than allowing for the anatomic divisions of the skin, it is preferable to consider a superficial layer 1 mm thick through which heat exchange occurs only by conduction, and a deep layer including part of the dermis and the subcutaneous adipose tissue, through which heat exchange occurs by conduction and blood convection. The average thickness of the subcutaneous fat is therefore given by the formula:

$$e \text{ mm} = (\text{average skinfold} - 2)0.5 \qquad (2)$$

The sum total of research on the thermal conductivity of the human body during immersion clearly demonstrates the importance of peripheral circulatory reactions and subcutaneous fat in protecting the body against cold. On the other hand, data on conductivity in the zone of thermal neutrality in water are not very numerous due to the inaccuracies involved in definition of this zone. According to Burton and Edholm (1955), the water temperature representing thermal neutrality is 35°C. These investigators go so far as to state that in order to maintain thermal equilibrium the water should be at 36°C, at which the subject experiences a comfortable sensation of warmth. As criteria of thermal neutrality, Craig and Dvorak (1966) use an average /194
constant body temperature and a heart rate slightly below the heart rate at rest in air, due to the slight bradycardia caused by immersion. According to these investigators, the zone of neutrality is between 35 and 35.5°C. However, it should be noted that their experiments lasted only one hour, after a rest period of only 20 minutes at the laboratory temperature. Thus these subjects did not reach a stable state. As a result, the conductivity values

given in the literature are 39.4 W/m^2 °C according to Craig and Dvorak and 20.9 to 31.4 W/m^2 °C according to Rennie (Table 1). These values are relatively high and are observed in air only in individuals subjected to hot environments. The observations of these investigators may have been partially distorted due to an insufficient preliminary rest period (20 minutes, rather than the usual 90 minutes), resulting in an erroneous interpretation of the slight drop in rectal temperature in baths at temperatures slightly below 35°C. It was for this reason that we determined the zone of thermal neutrality in agitated water, using 11 fasting subjects after a rest period of 90 minutes in a reclining position in air at a temperature in the vicinity of thermal neutrality (Boutelier et al., 1971). The criteria chosen were as follows: constant metabolism, equal or extremely close to that measured in air after 90 minutes of rest in a reclining position: 44 to 46 W/m^2; a drop of no more than 0.25 to 0.30°C in rectal temperature during the first two hours of immersion, this temperature subsequently remaining constant at 36.7 to 36.8°C; a normal distribution of local skin temperatures such as that described by Winslow and Herrington (1949); and a linear relationship with a gradient of 1 between the average skin temperature and the temperature of the water. This relationship is drawn from the Newtonian equation, which, assuming the body to be completely immersed, may be stated as follows:

$$\bar{T}_s = T_{H_2O} + C/h_c \tag{3}$$

Under these conditions, the thermal conductivity should be close to that obtained in air: 14-15 W/m^2 °C. The results obtained in 30 experiments show that the zone of thermal neutrality in water ranges from 33-34°C for all water flow rates. Thus the "thermal profile" of man is as follows: T_{re} = 36.7-36.8°C, $\bar{T}_s$ = 34 ± 0.10°C, M = 48 ± 1.7 W/m^2 and h_b = 16.7 ± 0.9 W/m^2 °C. These values may vary slightly with the physical condition of the subject, especially his/her age. The quantity of subcutaneous adipose tissue

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TABLE 1. BODY CONDUCTIVITIES FOR SUBJECTS UNDER IMMERSION AS GIVEN IN THE LITERATURE

Investigator	T_{H_2O} °C	Thickness of subcutaneous fat in mm	h_b W/m² °C	Observations
Lefevre (1901)	5		14.13	Values calculated from the conductivities of the skin and subcutaneous tissue.
	12		8.23	
	18		11.33	
	24		9.49	
	30		7	
Burton et al. (1936)	33		7.17*	[illegible]
	36		36.96*	
Carlson et al. (1958)	10		2.56	Minimum conductivity observed in an obese subject.
Cannon and Keatinge (1960)	12.5	12.5	4.13*	The thickness of the adipose tissue was calculated on the basis of measurements of the skinfold.
	16		4.91*	
	28	2.35	10.26*	
	33	2.25	14.54*	
Rennie et al., (1962)	33	6.5	10.46*	
	35	6.5	20.93*	White Americans (5 [illegible] subjects).
	33	1.5	17.44*	
	35	1.5	31.4	Eskimos.
Rennie et al. (1962)	30	3.8	6.66*	American men and women (12 subjects)
	33		12.41*	
	30	2.24	9.10*	
	31		8.94*	Diving women (6 subjects)
Craig and Dvorak (1966)	24	5.4 ± 1.4	10.47*	Averages for 10 subjects immersed for one hour
	26		11.40*	
	28		11.98*	
	30		11.05*	
	32		13.60*	
	34		21.28*	
	35		39.40*	
Boutelier et al. (1968)	20°C	# 10	4.77	Minimum conductivity of a fat subject
	18		11.86	Average of 5 subjects
	25–27°C		8.60	Average of 11 subjects
	33–34°C		16.7±0.9	
Inoue (1972)	24.7	6.8	3.34*	One-hour tests performed in the summer on Japanese subjects
	27.1	5.1	6.32*	
	30.5	2.5	10.07*	
	30.5	1	7.75*	
	30.6	1.3	7.50*	
	31.5	2.3	9.85*	
	31.9	1.2	8.51*	

* The values marked with an asterisk are values calculated by dividing the heat loss of the body by the center-water temperature difference.

does not seem to have any effect, on the other hand. This finding is in agreement with that of Cannon and Keatinge (1960), who observed that the threshold water temperature at which the metabolic rate begins to increase is the same for fat subjects as for thin subjects. One may therefore assume that at thermal neutrality, heat exchange by conduction through the subcutaneous adipose tissue is extremely slight in comparison with the exchange by blood convection within the dermis. The peripheral circulation short-circuits the subcutaneous fat to some extent, by means of the arteries which pass through it to feed the dermal arteriolar plexuses. /196

This review of the literature shows that the values obtained for the thermal conductivity of the body as a function of water temperature are widely scattered, both in the zone of thermal neutrality and in a cold environment. In regard to the zone of thermal neutrality, the scattering basically depends on differences in the neutrality criteria used by different investigators. In a cold environment, although a rough approximation of the conductivity variations given by Burton is obtained, the values may remain the same or vary by a factor of two or more for the same water temperature. Different experimental conditions, the variability between individuals and racial differences seem to be the causes of this scattering, which makes it difficult to interpret the results and use these values to design models. For this reason we have undertaken a systematic study of the thermal conductivity of the body on ten nude subjects, the results of which will be presented and discussed below.

III. Experiment

A. Method

The immersion tests were performed in the morning, using the following protocol: having fasted since the preceding evening, the subject, wearing swimming trunks, was placed at rest in a reclining position in agitated water at a neutral temperature (33.2 ± 0.1°C) for 90 minutes. The temperature of the bath was then decreased as quickly as possible to the temperature chosen for the experiment -- 32, 31, 28, 26 or 24°C -- and kept at this level for 120 minutes. Body temperatures (ten skin temperatures and the rectal temperature) were recorded once a minute from the beginning of the experiment. The metabolism was measured once every ten minutes, counting from the 60th minute of rest, by the analysis of exhaled gases sampled for four minutes. Ten subjects were used; their biometric characteristics are given in Table 2. /197

TABLE 2. BIOMETRIC CHARACTERISTICS OF SUBJECTS

Subject	Age	Weight kg	Height m	Surface area m^2	Skin-fold mm	Thickness of subcutaneous fat mm
Ad.	36	80	1,71	1,92	20,4	9.2
Po.	36	81,4	1,72	1,93	19,8	8,9
Yo.	25	73	1,73	1.86	16,6	7,3
Ra.	23	77,7	1,70	1,89	15,9	6,95
Bo.	38	77,5	1,71	1,88	12,9	5,45
Le.	24	62,5	1,64	1,67	11,6	4,8
Sa.	27	72,8	1,70	1,84	11,0	4.5
Ro.	39	72,8	1.78	1,90	11,0	4,5
Nu.	23	69,1	1,74	1,82	5,3	1,65
Ja.	29	55,5	1.74	1.66	4.5	1.25

B. Experimental Results

Two conductivities were calculated, one for the immersed part of the body, hb_{im}, and other for the entire body, h_b. We felt this was necessary since in cold water one generally observes vasodilation in the non-immersed surface, while there is complete peripheral vasoconstriction over the rest of the body.

At thermal neutrality, the mean h_{bim} was 14.83 ± 1.91 W/m^2 °C, and h_b was 16.09 ± 1.89 W/m^2/°C. The latter value was not statistically different from that given in Table 1, obtained from another group of subjects. As in the tests for determination of the thermal neutrality zone, there does not seem to be any difference between fat subjects and thin subjects. The quantity of heat furnished to the skin by metabolism was 46.17 ± 4.7 W/m^2, the rectal temperature was 36.79 ± 0.23°C, and the average skin temperature was 33.92 ± 0.17°C. /198

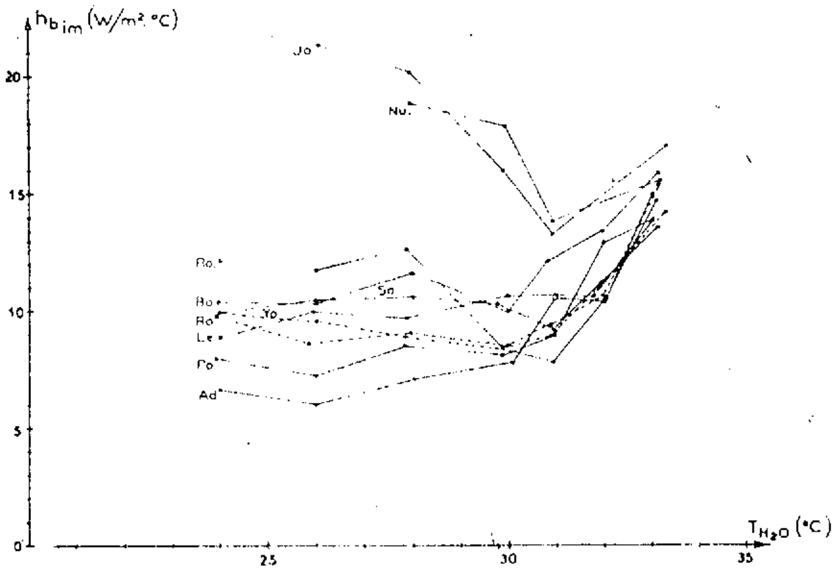

Fig. 1. Variations in the heat transfer coefficient of the body as a function of water temperature.

In a cold environment, the evolution of the thermal conductivity as a function of water temperature may be broken down into two parts: a zone of rapid decrease to neutrality ranging to 30 or 31°C for most of the subjects, and a zone of stabilization or increase, depending on the quantity of adipose tissue (Fig. 1).

In the zone of decrease, a significant linear relationship between conductivity and water temperature was found in seven out of ten subjects. This could not be observed in the other three subjects, either because h_b reached a minimum value in a 31°C bath (thin subject) or because this minimum value could not be determined accurately. The water temperature in which minimum conductivity was observed depended on the thickness of the skin-fold, but there were variations between individuals which may be attributed to more or less intense circulatory reactions. Furthermore, the minimum values for the overall conductivity h_b and the conductivity of the immersed part of the body $h_{b_{im}}$ depended on the thickness of the subcutanous fat e_g, expressed in mm, as shown by the following relationships:

$$h_b = -0.873\ eg + 14.65 \quad r = 0.89 \quad n = 10 \tag{4}$$

$$h_{b_{im}} = -0.847\ eg + 13.89 \quad r = 0.91 \quad n = 10 \tag{5}$$

These relationships are significant at $p < 0.01$. Within the water temperature range in which conductivity decreased, it was not possible to discover any relationship between the heat losses from the skin ($M - H_{Res}$) and the conductivity.

For baths whose temperature was between 30 or 31°C and 24°C, there was no significant relationship between conductivity and water temperature for five subjects out of ten and the conductivity remained at its minimum value. However, for the three thinnest subjects the conductivity increased significantly as the temperature of the water was lowered, while for two other subjects it decreased slightly. In addition, in only four subjects there was a significant linear relationship between conductivity and heat losses through the skin, but the gradients of these relationships were quite weak for the two subjects with thick adipose tissue (subjects Io and Le). Finally, a comparison of the conductivities for different subjects in a single environment shows the conductivity of thin subjects is always much higher than that of fat subjects.

IV. Discussion

One may be surprised at the lack of any relationship between conductivity and heat losses in the temperature zone between thermal neutrality and 30 or 31°C, since according to the equation for computing h_b (equation 1), this coefficient should be a function of $(M - H_{res})$ and $(T_{re} - \bar{T}_s)$. However, the heat losses through the skin are virtually constant and roughly equal to the measured values obtained at thermal neutrality (Boutelier, 1973); the same is true of $(M - H_{res})$ since there is a heat balance. The conductivity must therefore be inversely proportional to $(T_{re} - \bar{T}_s)$. Within this water temperature range, the variations in rectal temperature of most of the subjects were slight in comparison to that of the average skin temperature. The decrease in average skin temperature was 13-14 times greater, for example, than that of the rectal temperature between thermal neutrality and a 31°C bath. It follws that hb must be primarily a function of the variations in $\bar{T}_s$, and thus of the water temperature, since there is a linear relationship between $\bar{T}_s$ and T_{H_2O} (Boutelier, 1973). However, the relationship between conductivity and ambient temperature may be interpreted differently. The body may be said to combat the decrease in ambient temperature by reducing its conductivity by means of peripheral vasoconstriction, without falling back on an increase in metabolic rate entailing heat losses, and consequently without producing shivering. This circulatory regulation is progressive, but it quickly reaches a maximum, since the water temperature range within which it operates is quite restricted: 33.5 to approximately 30 °C. This range depends on the thickness of the subcutaneous adipose tissue. The thinner this layer, the narrower the zone within which this regulation occurs. /199

In the water temperature zone ranging from 30 to 24°C, the conductivity remains at its minimum level or undergoes little variation for subjects whose adipose tissue is thicker than approximately 4 mm. Thus the conductivity is not related to T_{H_2O}, $\bar{T}_s$ or $(T_{re} - \bar{T}_s)$, nor is it related to heat loss. This stability can be explained only by a variation in heat losses proportional to the variation in the difference $(T_{re} - \bar{T}_s)$, that is, in $\bar{T}_s$, since the variation in $\bar{T}_s$ from its value at neutrality and the value it reaches within this water temperature range is 12-15 times greater than that of the rectal temperature. The rectal temperature of these subjects scarcely varies from its value at thermal neutrality, due to its increase in the transitional period. On the other hand, the significant increase in conductivity in thin subjects is due to an increase in heat losses which is greater than the increase in the difference $(T_{re} - \bar{T}_s)$, since the drop in rectal temperature tends to reduce the center-periphery temperature difference.

The variations in thermal conductivity of the body reveal the essential role of peripheral vasoconstriction and subcutaneous fat, a fact which has already been pointed out by a number of investigators. One is tempted to state that h_b provides a direct picture of peripheral circulatory phenomena and that its minimum value corresponds to maximum vasoconstriction. However, it is difficult to explain its considerable increase in thin subjects by superficial vasodilation, since this has not been observed. One may therefore assume, with Lefevre (1901), that this increase is due to a signi- /200
ficant increase in muscular conductivity provoked by intense shivering. In other words, one can assume the body to be composed of three main compartments (Fig. 2): a center consisting of the viscera and the skeleton, a muscular zone and a periphery including the subcutaneous fat and the skin, reduced to the epidermis and part of the dermis or a thickness of approximately 1 mm. Three heat transfer coefficients are associated with these compartments: h_n for the center, h_m for the muscle and $h_{s.g}$ for the periphery. The coefficient h_b represents a combination of these three conductivities, and a constant or minimum value for this conductivity does

not mean that the elements which make it up are constant or minimum also. Thorough study of these variations is possible, therefore, only if the average temperatures and heat outputs of each of these regions are known. However, some idea of the variations in overall center-muscular region conductivity $h_{n\cdot m}$ may be obtained by assuming that the heat flow in each region is perpendicular to the surface and that the heat output in the peripheral zone and the decrease in area from the skin to the superficial muscular region are negligible. At thermal neutrality, the subcutaneous adipose tissue is virtually short-circuited, since there is no appreciable difference in h_b from one subject to the next. The peripheral conductivity is therefore reduced to the conductivity of the wet skin h_s. The heat furnished by metabolism is transmitted by blood convection to the level of the subpapillary or arterial plexus, until it reaches the uppermost layer of the skin, through which it passes by conduction. Since the thermal resistances of these two regions are in series, one may write:

$$h_{b} = h_s \times h_{n\cdot m}/(h_s + h_{n\cdot m}) \tag{6}$$

from which the following may be derived:

$$h_{n\cdot m} = h_s \times h_{b}/(h_s - h_{b}) \tag{7}$$

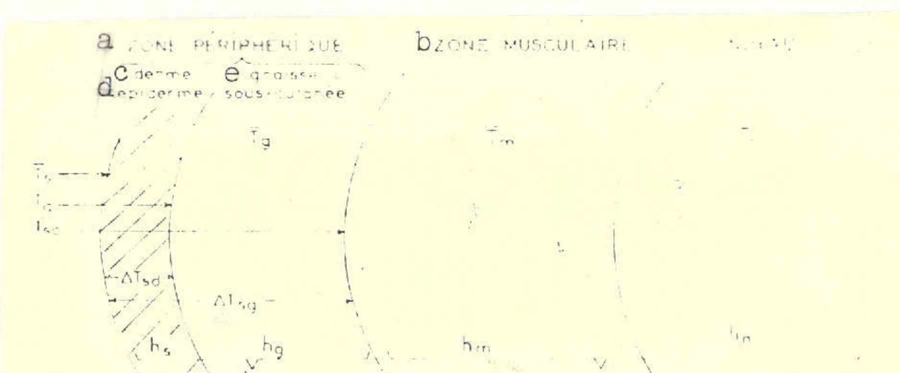

Fig. 2. Diagram showing the various zones of the body with their conductivities and average temperatures.

Key. a. Peripheral zone; b. Muscular zone; c. Dermis; e. Epidermis; e. Subcutaneous fat

Within the water temperature range in which losses are roughly constant, h_b varies only as a function of the variations in /201 average skin temperature. One may therefore assume that only the peripheral component of h_b varies and that $h_{n\cdot m}$ remains stable at its neutrality value, since the metabolism does not increase. The peripheral conductivity $h'_{s\cdot g}$ is therefore given by the equation:

$$h'_{s\cdot g} = h_b \times h_{n\cdot m_{neutr.}}/(h_{n\cdot m_{neutr.}} - h_b) \tag{8}$$

This type of calculation may be used to determine the significance of the peripheral vasoconstriction, based on the data given by Bazett and McGlone (1927). When peripheral vasoconstriction is complete, $h'_{s\cdot g}$ reaches its minimum value $h_{s\cdot g}$, which depends on the thickness of the subcutaneous fat, and the only variable element in h_b is $h_{n\cdot m}$, which can be determined by means of the equation:

$$h_{n\cdot m} = h_b \times h_{s\cdot g}/(h_{s\cdot g} - h_b) \tag{9}$$

To solve these equations it is necessary to know the conductivities of the skin h_s and the subcutaneous fat h_g, based on the thermal conductivity measurements of these tissues given in the literature. In accordance with the work of Lefevre (1901), Burton (1955), Buettener (1951), Hensel and Bender (1956), and Lipkin and Hardy (1954), the thermal conductivity of living, non-irrigated skin a maximum of 4 mm thick may be assumed to fall between 0.293 and 0.335 $W_{.m}/m^2/°C$. During immersion this conductivity is undoubtedly modified by imbibition by the stratum corneum, and thus we have assumed a conductivity of 322 $W/m^2/°C$ for the superficial part of the skin (1 mm thick). Furthermore, the average conductivity of fat is 0.209 $W/m^2/°C$ (Hardy and Soderstrom, 1938; Hatfield and Pugh, 1951). Using these values and knowing the thickness of the subcutaneous fat, it is possible to calculate the minimum peripheral conductivity $h_{s \cdot g}$:

$$h_{s \cdot g} = h_s \times h_g / (h_s + h_g) \qquad (10)$$

Such calculations show that the peripheral conductivity decreases by a factor of 15.7 in a fat subject (subcutaneous fat 9.2 mm thick), while it decreases by a factor of only three in a thin subject (subcutaneous fat 1.25 mm thick) in the change from thermal neutrality to the state of maximum peripheral vasoconstriction. In addition, the variations in the components of the overall conductivity of the body with water temperature may be analyzed by solving equations 7-9. Fig. 3 shows their variations and that of the total conductivity h_g for three subjects with skinfolds of different thickness. It may be noted that the minimum h_b coincides with the minimum peripheral conductivity $h_{s \cdot g}$ only in the thin subject (curve 3). In the other two subjects (curves 1 and 2), $h_{s \cdot g}$ reaches a minimum at a higher water temperature (30-32°C) than that at which the minimum h_b is observed. This indicates that the conductivity of the center-muscular region de- /202 creases when $h_{s \cdot g}$ has reached its minimum value. The evolution of this conductivity is characterized by a decrease which is stronger as the subcutaneous adipose tissue is more developed, followed by an increase which is especially sharp in thin subjects. Thus in subject Ja (curve 3), $h_{n \cdot m}$ increases 33% in a 26°C bath, while in subject Po (curve 1) it is still 37% lower than its value /203 at neutrality. It should also be pointed out that with an equal thermal load, the same evolution in this partial conductivity is observed in both fat and thin subjects. Plotting the variations of conductivity as a function of water temperature merely reveals the fact that, at a given water temperature, the heat loss by a fat subject is not as high as that of a thin subject. In a 26°C bath, for example, subject Ja lost 166 W/m^2 while subject Po lost only 74 W/m^2.

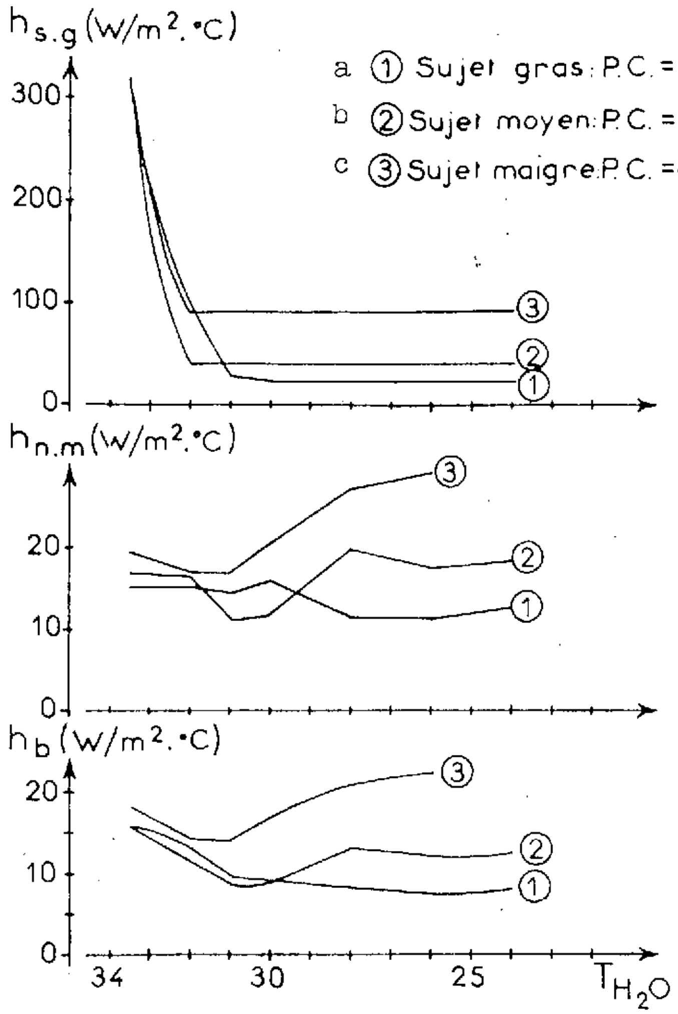

Fig. 3. Evolution of partial conductivities of a fat subject (1), a medium-weight subject (2), and a thin subject (3) as a function of bath temperature. It should be noted that the minimum h_b does not correspond to the minimum $h_{s \cdot g}$. One may also note the decrease in h_{nm}, followed by its increase, which was especially fast in the thin subject.

Key. a. Fat subject: P.C. = 20 mm
b. Average-weight subject: P.C. = 11 mm
c. Thin subject: P.C. = 4.5 mm

The decrease in center-muscular region conductivity may be interpreted as the result of cooling of the muscular areas closest to the surface and the storage of heat in the center, provoked by the peripheral vasoconstriction. These two factors help to raise the temperature difference between the center and the surface of the muscles, and the increase in metabolism and muscular conductivity is insufficient to compensate for this phenomenon. It therefore appears that the superficial muscular cooling singled out as a racial characteristic in adaptation to cold (Innoue, 1972) may also be found in non-adapted European subjects. The increase in conductivity h_{nm} for high heat losses may be explained by a significant increase in metabolism, blood circulation in the most active muscular region, and a lowering of the temperature difference between the center and the muscular surface due to the heat deficit in the center. This is observed in thin subjects at much higher bath temperatures than in fat subjects, due to the weak protection provided by the peripheral zone and to the heat deficit occurring in the center.

V. Conclusion

This report has revealed the following findings:

At thermal neutrality in water, the thermal conductivity of the body is close to that observed in air and variations between individuals are slight. The quantity of subcutaneous adipose tissue does not seem to have any detectable effect.

In cold water, the conductivity of the body decreases rapidly under the influence of cutaneous vasoconstriction, which interposes the insulating layer represented by the subcutaneous fat between the center and the surface of the body. As a result, conductivity varies widely from one subject to the next and depends on the thickness of this layer.

An analysis of variations in the various components of the overall conductivity as a function of water temperature shows that cutaneous vasoconstriction alone has a limited effect. The cooling

reaches the most superficial region of the muscles, which /204
contribute to the peripheral insulation, a phenomenon which had previously been considered a characteristic of adaptation to cold.

The increase in conductivity noted especially in thin subjects is due to an increase in the conductivity of the center-muscular region zone, probably produced by increased circulation and increased heat output, primarily in the muscles.

Given the complex nature of the thermal conductivity of the body, it seems hazardous to try to obtain an index of the peripheral circulation from conductivity variations in a cold environment. With knowledge of the variations in partial conductivities as a function of thermal load, it should be possible to perform additional deep temperature measurements (muscular and subcutaneous) to evaluate the convection component due to the blood circulation in different areas.

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